

Towards an explanation of transverse single-spin asymmetries in proton-proton collisions: the role of fragmentation in collinear factorization

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We study the transverse single-spin asymmetry for single-hadron production in proton-proton collisions within the framework of collinear twist-3 factorization in Quantum Chromodynamics. By taking into account the contribution due to parton fragmentation we obtain a very good description of all high transverse-momentum data for neutral and charged pion production from the Relativistic Heavy Ion Collider. Our study may provide the crucial step towards a final solution to the long-standing problem of what causes transverse single-spin asymmetries in hadronic collisions within Quantum Chromodynamics. We show for the first time that it is possible to simultaneously describe spin/azimuthal asymmetries in proton-proton collisions, semi-inclusive deep-inelastic scattering, and electron-positron annihilation by using collinear twist-3 factorization in the first process along with transverse momentum dependent functions extracted from the latter two reactions.

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Introduction The field of transverse single-spin asymmetries (SSAs) in hard semi-inclusive processes began some four decades ago with the observation of the large transverse polarization (up to about 30%) of neutral Λ -hyperons in the process $pBe \rightarrow \Lambda^\dagger X$ at FermiLab [1]. People noticed early on that the naïve collinear parton model cannot generate such large effects [2]. It was then pointed out that SSAs for single-particle production in hadronic collisions are genuine twist-3 observables for which, in particular, collinear 3-parton correlations have to be taken into account in order to have a proper description within Quantum Chromodynamics (QCD) [3]. This formalism later on was worked out in more detail and also successfully applied to SSAs in processes like hadron production in proton-proton collisions, $p^\dagger p \rightarrow hX$ — see, e.g., Refs. [4–10]. Here we focus on SSAs in such reactions, which were extensively investigated in fixed target and in collider experiments.

Let us now look at the generic structure of the spin-dependent cross section for $A(P, \vec{S}_\perp) + B(P') \rightarrow C(P_h) + X$, where the 4-momenta and polarizations of the incoming protons A, B and outgoing hadron C are specified. In twist-3 collinear QCD factorization one has

$$\begin{aligned} d\sigma(\vec{S}_\perp) = & H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} \\ & + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} \\ & + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)}, \end{aligned} \quad (1)$$

with $f_{a/A(t)}$ ($f_{b/B(t)}$) indicating the distribution function associated with parton a (b) in proton A (B), while $D_{C/c(t)}$ represents the fragmentation function associated with hadron C in parton c . The twist of the functions is denoted by t . The hard factors corresponding to each term are given by H, H' , and H'' , and the symbol \otimes represents convolutions in the appropriate momentum fractions. In Eq. (1) a sum over partonic channels and parton

flavors in each channel is understood.

The first term in (1) has already been studied in quite some detail in the literature [5, 7–12]. It contains both quark-gluon-quark correlations and tri-gluon correlations in the polarized proton, where for the former one needs to distinguish between contributions from so-called soft gluon poles (SGPs) and soft fermion poles (SFPs). The second term in (1), arising from twist-3 effects in the unpolarized proton, was shown to be small [13]. Only recently a complete analytical result was obtained for the third term in (1), which describes the twist-3 contribution due to parton fragmentation [14].

For quite some time many in the community believed that the first term in (1) dominates the transverse SSA in $p^\dagger p \rightarrow hX$ (typically denoted by A_N) for the production of light hadrons (see, e.g., Refs. [5, 7, 10]), where the SGP contribution is generally considered the most important part. Note that the SGP contribution to A_N is determined by the Qiu-Sterman function T_F [4, 5], which can be related to the transverse-momentum dependent (TMD) Siverson parton density f_{1T}^\perp [15, 16]. For a given quark flavor q , these entities satisfy [17]

$$T_F^q(x, x) = - \int d^2 \vec{p}_\perp \frac{\vec{p}_\perp^2}{M} f_{1T}^{\perp q}(x, \vec{p}_\perp^2) \Big|_{\text{SIDIS}}, \quad (2)$$

where M is the nucleon mass. Because of the relation in (2), one can extract T_F from data on either A_N or on the Siverson transverse SSA in semi-inclusive deep-inelastic scattering (SIDIS) $A_{\text{SIDIS}}^{\text{Siv}}$. It therefore came as a major surprise when an attempt failed to simultaneously explain both A_N and $A_{\text{SIDIS}}^{\text{Siv}}$ [11]. The striking result pointed out in Ref. [11] was that the two extractions for T_F differ in sign. This “sign-mismatch” puzzle could not be resolved by more flexible parameterizations of f_{1T}^\perp [18]. Also tri-gluon correlations are unlikely to fix

this issue [12], while SFPs may play some role [9].

At this point one may start to question the dominance of the first term in (1). In fact, data on the transverse SSA in inclusive DIS [19, 20] seem to support this point of view, i.e., that the first term in (1) is not the main cause of A_N [21]. Therefore, in the present work we study the potential role of the twist-3 fragmentation part of (1). After fixing the SGP contribution to A_N through the Siverson function extracted from data on $A_{\text{SIDIS}}^{\text{Siv}}$ [22, 23] and the relation in (2), we obtain a very good fit to all high transverse-momentum forward-region pion data for A_N from the Relativistic Heavy Ion Collider (RHIC). As explained below in more detail, our analysis shows for the first time that one can simultaneously describe A_N using collinear factorization, $A_{\text{SIDIS}}^{\text{Siv}}$, the Collins transverse SSA $A_{\text{SIDIS}}^{\text{Col}}$ in SIDIS, and $A_{e^+e^-}^{\cos(2\phi)}$ that represents a particular azimuthal asymmetry in electron-positron annihilation into two hadrons, $e^+e^- \rightarrow h_1 h_2 X$ [24].

Fragmentation contribution to A_N The fragmentation contribution to the cross section in (1) reads [14]

$$\begin{aligned} \frac{P_h^0 d\sigma(\vec{S}_\perp)}{d^3\vec{P}_h} = & -\frac{2\alpha_s^2 M_h}{S} \epsilon_{\perp, \alpha\beta} S_\perp^\alpha P_{h\perp}^\beta \sum_i \sum_{a,b,c} \int_{z_{\min}}^1 \frac{dz}{z^3} \\ & \times \int_{x'_{\min}}^1 \frac{dx'}{x'} \frac{1}{x} \frac{1}{x'S + T/z} \frac{1}{-x'\hat{t} - x\hat{u}} h_1^a(x) f_1^b(x') \\ & \times \left\{ \left[\hat{H}^{C/c}(z) - z \frac{d\hat{H}^{C/c}(z)}{dz} \right] S_{\hat{H}}^i + \frac{1}{z} H^{C/c}(z) S_H^i \right. \\ & \left. + 2z^2 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{C/c, \Im}(z, z_1) \frac{1}{\xi} S_{\hat{H}_{FU}}^i \right\}, \quad (3) \end{aligned}$$

where i denotes the channel, $x = -x'(U/z)/(x'S + T/z)$, $x'_{\min} = -(T/z)/(U/z + S)$, $z_{\min} = -(T + U)/S$, and $\xi = (1 - z/z_1)$. Here we used the Mandelstam variables $S = (P + P')^2$, $T = (P - P_h)^2$, and $U = (P' - P_h)^2$, which on the partonic level give $\hat{s} = xx'S$, $\hat{t} = xT/z$, and $\hat{u} = x'U/z$. Oftentimes one also uses $x_F = 2P_{hz}/\sqrt{S}$, where P_{hz} is the longitudinal momentum of the hadron, as well as the pseudo-rapidity $\eta = -\ln \tan(\theta/2)$, where θ is the scattering angle. The variables x_F , η are further related by $x_F = 2P_{h\perp} \sinh(\eta)/\sqrt{S}$, where $P_{h\perp}$ is the transverse momentum of the hadron. The non-perturbative parts in (3) are the transversity distribution h_1 , the unpolarized parton density f_1 , and the three (twist-3) fragmentation functions (FFs) \hat{H} , H , and \hat{H}_{FU}^{\Im} , with the last one parameterizing the imaginary part of a 3-parton correlator. The definition of those functions and the results for the hard scattering coefficients S^i can be found in [14]. (An alternative notation of the relevant FFs is given in Ref. [25], where twist-3 effects in SIDIS were computed.) We note that the so-called derivative term in (3), associated with $d\hat{H}/dz$, was first obtained in [26].

The function \hat{H} is related to the TMD Collins function

H_1^\perp [27] according to [14, 26]

$$\hat{H}^{h/q}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^{\perp h/q}(z, z^2\vec{k}_\perp^2). \quad (4)$$

This relation can be considered the fragmentation counterpart of Eq. (2). Exploiting the universality of the Collins function [28], one can simultaneously extract H_1^\perp and h_1 from data on $A_{\text{SIDIS}}^{\text{Col}}$ [29, 30] and data on $A_{e^+e^-}^{\cos(2\phi)}$ [31, 32] (see [33] and references therein). Below we utilize such information for H_1^\perp and h_1 when describing A_N . The FFs in (3) are related via [14]

$$H^{h/q}(z) = -2z\hat{H}^{h/q}(z) + 2z^3 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{h/q, \Im}(z, z_1), \quad (5)$$

implying that in the collinear twist-3 framework one has two independent FFs. It is important to realize that this is different from the so-called TMD approach for A_N , where only H_1^\perp enters the fragmentation piece [34].

Phenomenology of A_N for pion production We consider A_N for $p^\uparrow p \rightarrow \pi X$ in the forward region of the polarized proton, which has been studied by the STAR [35–37], BRAHMS [38, 39] and PHENIX [40] collaborations at RHIC. We mainly focus on data taken at $\sqrt{S} = 200$ GeV for which typically $P_{h\perp} > 1$ GeV. Throughout we use the GRV98 unpolarized parton distributions [41] and the DSS unpolarized FFs [42]. Note that the GRV98 parton distributions were also used in Refs. [22, 23, 33] for extracting the Siverson function and the transversity, which we take as input in our calculation. The SGP contribution to (1) is computed by fixing T_F through Eq. (2) with two different inputs for the Siverson function — SV1: f_{1T}^\perp from Ref. [22], obtained from SIDIS data on $A_{\text{SIDIS}}^{\text{Siv}}$ [43, 44]; and SV2: f_{1T}^\perp from Ref. [23], “constructed” such that, in the TMD approach, the contribution of the Siverson effect to A_N is maximized while maintaining a good description of $A_{\text{SIDIS}}^{\text{Siv}}$. These two inputs for f_{1T}^\perp are mainly distinct by their quite different large- x behavior. To compute the contribution in (3) we take h_1 and H_1^\perp (which fixes \hat{H} through (4)) from [33]. For favored fragmentation into π^+ we make for \hat{H}_{FU}^{\Im} the ansatz

$$\begin{aligned} \frac{\hat{H}_{FU}^{\pi^+/(u,\bar{d}), \Im}(z, z_1)}{D^{\pi^+/(u,\bar{d})}(z) D^{\pi^+/(u,\bar{d})}(z/z_1)} = & \frac{N_{\text{fav}}}{2I_{\text{fav}} J_{\text{fav}}} z^{\alpha_{\text{fav}}}(z/z_1)^{\alpha'_{\text{fav}}} \\ & \times (1-z)^{\beta_{\text{fav}}} (1-z/z_1)^{\beta'_{\text{fav}}}, \quad (6) \end{aligned}$$

with the parameters N_{fav} , α_{fav} , α'_{fav} , β_{fav} , β'_{fav} and the unpolarized FF D . Note that the allowed range for z and z/z_1 is $[0, 1]$ [45] and that our ansatz satisfies the constraint $\hat{H}_{FU}(z, z) = 0$ [45, 46]. With the use of DSS FFs [42], the factor I_{fav} reads $I_{\text{fav}} \equiv I_{u+\bar{u}} - I_{\bar{u}}$ where I_i

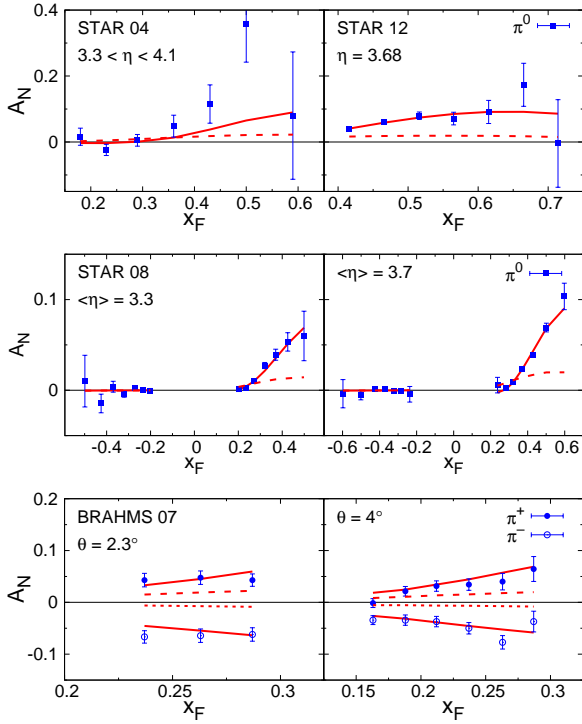


FIG. 1. Fit results for $A_N^{\pi^0}$ (data from [35–37]) and $A_N^{\pi^\pm}$ (data from [38]) for the SV1 input. The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\mathfrak{S}}$ switched off.

($i = u + \bar{u}$, \bar{u}) is defined as

$$I_i = \frac{N_i(K_{1,\text{fav}} + \gamma_i K_{2,\text{fav}})}{B[2 + \alpha_i, \beta_i + 1] + \gamma_i B[2 + \alpha_i, \beta_i + \delta_i + 1]},$$

with $K_{1,\text{fav}} = B[\alpha'_{\text{fav}} + \alpha_i + 1, \beta'_{\text{fav}} + \beta_i]$, (7)

$$K_{2,\text{fav}} = B[\alpha'_{\text{fav}} + \alpha_i + 1, \beta'_{\text{fav}} + \beta_i + \delta_i],$$

and $B[a, b]$ the Euler β -function. The parameters N_i , α_i , β_i , γ_i , and δ_i come from D FFs at the initial scale and are given in Table III of [42]. Note that D^{π^+}/u in Ref. [42] differs from D^{π^+}/\bar{d} . J_{fav} in (6) is similarly defined as $J_{\text{fav}} \equiv J_{u+\bar{u}} - J_{\bar{u}}$, where J_i ($i = u + \bar{u}$, \bar{u}) follows from I_i through $\alpha'_{\text{fav}} \rightarrow (\alpha_{\text{fav}} + 4)$, $\beta'_{\text{fav}} \rightarrow (\beta_{\text{fav}} + 1)$. The factor $1/(2I_{\text{fav}}J_{\text{fav}})$ in (6) is convenient and implies $\int_0^1 dz z H_{(3)}^{\pi^+/u}(z) = N_{\text{fav}}$ at the initial scale, where $H_{(3)}$ represents the entire second term on the r.h.s. of (5). For the disfavored FFs $\hat{H}_{FU}^{\pi^+/(d,\bar{u}),\mathfrak{S}}$ we make an ansatz in full analogy to (6), introducing the additional parameters N_{dis} , α_{dis} , α'_{dis} , β_{dis} , β'_{dis} . (I_{dis} and J_{dis} are calculated using $D^{\pi^+}/d = D^{\pi^+}/\bar{u}$ from [42].) The π^- FFs are then fixed through charge conjugation, and the π^0 FFs are given by the average of the FFs for π^+ and π^- . The FFs $H^{\pi/q}$ are computed by means of (5). All parton correlation functions are evaluated at the scale $P_{h\perp}$ with leading order evolution of the collinear functions.

Using the MINUIT package we fit the fragmentation contribution to data for $A_N^{\pi^0}$ [35–37] and $A_N^{\pi^\pm}$ [38]. To facilitate the fit we only keep 7 parameters in $\hat{H}_{FU}^{\pi^+/q,\mathfrak{S}}$ free.

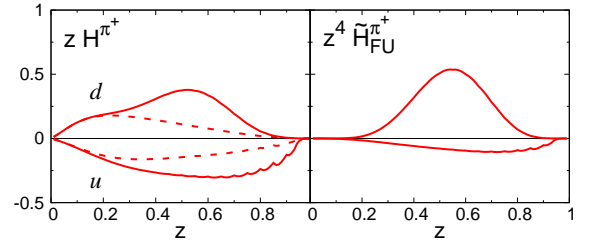


FIG. 2. Results for the FFs H^{π^+}/q and $\tilde{H}_{FU}^{\pi^+}/q$ (defined in the text) for the SV1 input. Also shown is H^{π^+}/q without the contribution from $\hat{H}_{FU}^{\mathfrak{S}}$ (dashed line).

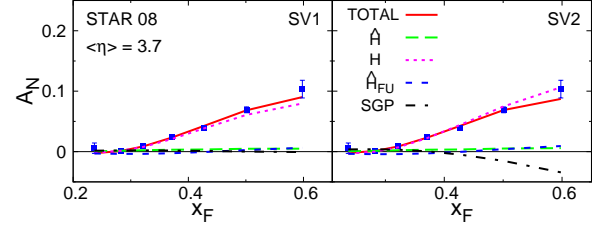


FIG. 3. Individual contributions to $A_N^{\pi^0}$ (data from [36]) for SV1 and SV2 inputs.

We also allow the β -parameters $\beta_u^T = \beta_d^T$ of the transversity to vary within the error range given in [33]. All integrations are done using the Gauss-Legendre method with 250 steps. For the SV1 input the result of our 8-parameter fit is shown in Tab. I. Note that the values for $\beta'_{\text{fav}} = \beta'_{\text{dis}}$ and β_{fav} are at their lower limits, which we introduce to guarantee a finite integration upon z_1 in (3) and a proper behavior of A_N at large x_F , respectively. For the SV2 input the values of the fit parameters are similar, with an equally successful fit ($\chi^2/\text{d.o.f.} = 1.10$).

TABLE I. Fit parameters for SV1 input.

$\chi^2/\text{d.o.f.} = 1.03$	
$N_{\text{fav}} = -0.0338$	$N_{\text{dis}} = 0.216$
$\alpha_{\text{fav}} = \alpha'_{\text{fav}} = -0.198$	$\beta_{\text{fav}} = 0.0$
$\beta'_{\text{fav}} = \beta'_{\text{dis}} = -0.180$	$\alpha_{\text{dis}} = \alpha'_{\text{dis}} = 3.99$
$\beta_{\text{dis}} = 3.34$	$\beta_u^T = \beta_d^T = 1.10$

The very good description of A_N is also reflected by Fig. 1. We emphasize that such a positive outcome is non-trivial if one keeps in mind the constraint in (5) and the need to simultaneously fit data for $A_N^{\pi^0}$ and $A_N^{\pi^\pm}$. Results for the FFs H^{π^+}/q and $\tilde{H}_{FU}^{\pi^+}/q \equiv \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{1-z_1} \frac{1}{\xi} \hat{H}_{FU}^{\pi^+/q,\mathfrak{S}}(z, z_1)$ are displayed in Fig. 2. In either case the favored and disfavored FFs have opposite signs. This is like for H_1^\perp where such reversed signs are actually “preferred” by the Schäfer-Teryaev (ST) sum rule $\sum_h \sum_{S_h} \int_0^1 dz z M_h \hat{H}^{h/q}(z) = 0$ [47]. Note that the ST sum rule, in combination with (5), implies a constraint on a certain linear combination of $H^{h/q}$ and (an

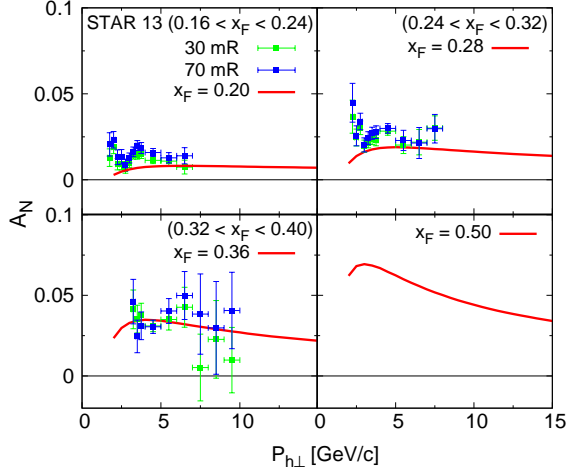


FIG. 4. A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [48]).

integral of) $\hat{H}_{FU}^{h/q,\mathfrak{S}}$. In view of that, reversed signs between favored and disfavored FFs like in Fig. 2 are actually beneficial. Also depicted in Fig. 2 is $H^{\pi^+/q}$ when $\hat{H}_{FU}^{\pi^+/q,\mathfrak{S}}$ is switched off. As shown in Fig. 1, in such a scenario, i.e., by turning off the 3-parton FF, one cannot describe the data for A_N . According to Fig. 3, the \hat{H} term (including its derivative) in (3) contributes only very little to A_N . Also the SGP pole term is small, except for the SV2 input at large x_F , where its contribution is opposite to the data. Clearly A_N is governed by the H -term in (3). This result can mainly be traced back to the hard scattering coefficients: e.g., for the dominant $qg \rightarrow qg$ channel one has $S_H \propto 1/\hat{t}^3$, but $S_{\hat{H}} \propto 1/\hat{t}^2$ [14] in the forward region where \hat{t} is small. Finally, Fig. 4 shows the $P_{h\perp}$ -dependence of A_N for $\sqrt{S} = 500$ GeV. Preliminary data from STAR, extending to almost $P_{h\perp} = 10$ GeV, show that A_N is rather flat [48]. The twist-3 calculation agrees with that trend, and also the magnitude of A_N is in line with the data. Note that the data of Ref. [48] were not included in our fit and that only statistical errors are shown in Fig. 4 [48].

Conclusions Collinear twist-3 QCD factorization can be considered the most natural and rigorous approach to the transverse SSA A_N in $p^\uparrow p \rightarrow hX$. However, the sign-mismatch issue of the Sivers effect had put this framework into question [11]. Here we have demonstrated for the first time that, despite the sign-mismatch problem, twist-3 factorization actually can describe high-energy RHIC data for A_N^π very well if one takes the fragmentation contribution into account. We re-emphasize that this result is non-trivial. Since in the twist-3 approach part of A_N can be fixed by spin/azimuthal asymmetries in SIDIS and in $e^+e^- \rightarrow h_1 h_2 X$, we have shown that at present a simultaneous description of all those observables is possible. We repeat that the fragmentation con-

tribution in twist-3 factorization goes beyond the pure Collins effect. Independent information on the FFs $H^{\pi/q}$, $\hat{H}_{FU}^{\pi/q,\mathfrak{S}}$ from other sources is needed before one can ultimately claim the intriguing data on A_N^π is fully understood. However, the fact that $\hat{H}_{FU}^{\pi/q,\mathfrak{S}}$ gives a reasonable contribution to (the numerically dominant) $H^{\pi/q}$ (see Fig. 2) allows one to be optimistic in this regard.

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